CHARGE DISTRIBUTION IN A QUASI-STATIC THUNDERCLOUD MODEL

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ABSTRACT

An analysis is made of the charge distribution in a quasi-static thundercloud system with the assumptions that (1) the cloud has a charge separation mechanism at its midpoint and (2) the conductivity within the cloud is reduced by a given fraction from the free-air conductivity remote from the storm. The charge separation mechanism produces the primary positive dipole of the storm. The analysis shows that the growth of the charge in the central cloud primary dipole is accompanied by the development of shielding layers of opposing sign charge at and about the cloud-air interface. A positive shielding charge distribution is established at the cloud base while a negative charge shielding distribution occurs about the upper cloud. The analysis permits an evaluation of the limiting charge magnitudes that exist outside the cloud boundary as a result of the unbalance of the positive and negative ion concentrations, and those that exist inside the cloud boundary principally as the result of deposition of charge on cloud particulates. The lower positive shielding charge completely accounts for the positive charge center often observed in the base of storms. The growth rates and total charge of the shielding charge distributions approximate the growth rate and total charge of the primary dipole. Following the lightning discharge, the shielding layer charge readjustment occurs at a more rapid rate, determined principally by the free-air conductivity.

1. INTRODUCTION

The true magnitude of the separated electric charges and their distribution in thunderclouds is not known. A frequent conclusion is that the total cloud charges are not of a different order of magnitude than the charges dissipated by lightning strokes. In other words, the average cloud charge is implied to be a small multiple of the charge carried to earth by ground strokes, or some 40 C. to 80 C. Recent measurements by Takeuti [14, 15], however, show that the charges neutralized by cloud discharges often exceed 100 C., thereby lending credence to the existence of charge centers of a few hundred coulombs in the thunderstorm structure.

A common concept of the charge distribution is a carryover from the pioneer measurements of Simpson and Robinson [13]. A primary vertical dipole of +24 C. and −20 C. occurs within the storm, the upper charge being positive, the lower negative, with a spatial separation of a few kilometers. A small positive cell of +4 C. is believed often evident near the cloud base. More recently, Kasemir [11] has computed the charges on the basis of continuity of current flow and has arrived at a charge distribution in which the upper cloud central core of positive charge is +60 C. while the lower central charge is −340 C. Researchers have pointed out that because of the difference in the electrical conductivity within and outside the cloud, a distribution of charge, of sign opposite that of the interior cloud, exists at the surface of clouds and acts to screen or mask the interior cloud charges to the exterior observer. As a result of these considerations the net cloud dipole as computed by Kasemir appears to approximate more nearly the Simpson-Robinson model when measurements are made, for example, of the electric field at the earth's surface near storms.

Measurements obtained by aircraft at cloud penetration and overflight altitudes have not clarified the charge distribution details (see Fitzgerald [3, 4] and Fitzgerald and Cunningham [5]). Overflight data generally reflect the positive dipole charge structure; in-cloud data, however, show that during a large fraction of the time, negative charge is still above the aircraft at flight altitudes of 9.1 km. Further, the flight data have been interpreted to show that no screening layer is evident at the cloud boundary.

There is no doubt that the existing theories of thunderstorm electrification suffer from lack of data despite the considerable measurement effort in the past two decades. The complex nature of the storm in its uncontrolled environment prevents truly fruitful measurements, but in spite of the complexities, we know that a systematic charge separation mechanism exists, which produces the observed accumulations of positive and negative charge that constitute the primary dipole charge distribution.

A first task toward understanding the thunderstorm mechanism is the evaluation of the charge distribution in and about the thunderstorm cloud-air system, on the assumption that the charge separation mechanism exists within the central cloud structure. In doing so, we will assume also a simplified cloud structure that has the property of being quasi-static over a time period equal or greater than the period important to the thunderstorm

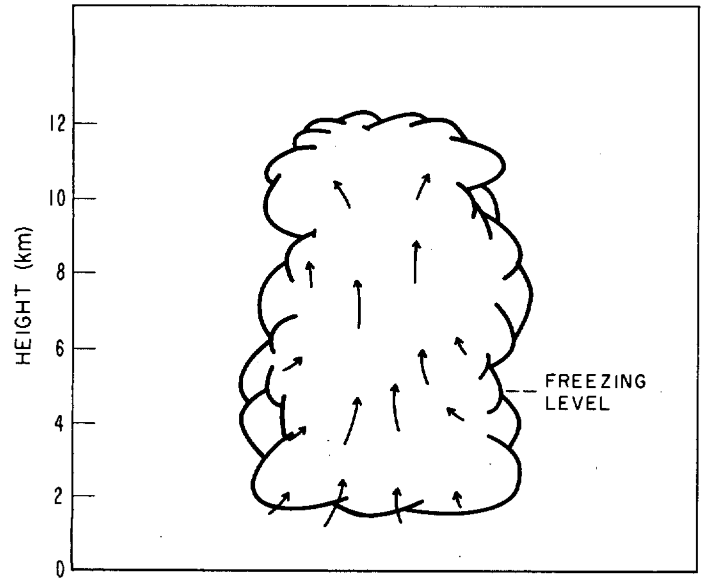

FIGURE 1.—Cloud model. Arrows indicate cloud motion.

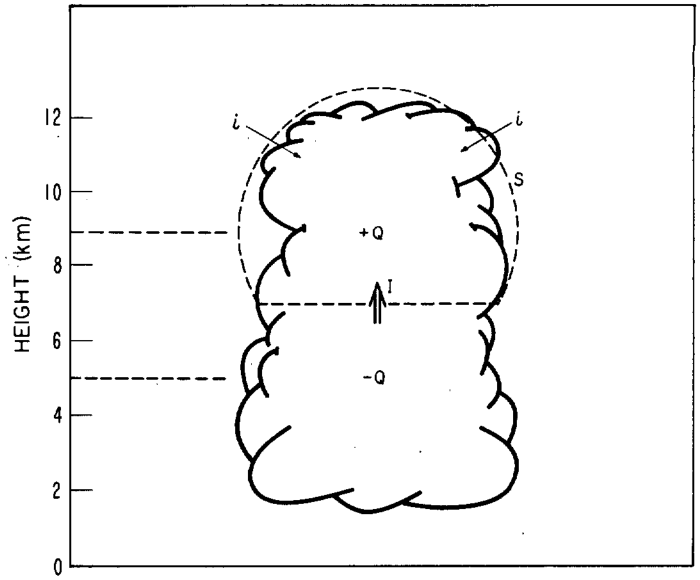

FIGURE 2.—Primary dipole charge distribution and current source I of cloud model.

electrification processes. The limitation imposed by this assumption will become clear during the discussion that follows. It is hoped that a clarification of certain of the more basic features of thundercloud electric processes will be gained, yielding a somewhat simplified picture and contributing to the final understanding of the thunderstorm electrification mechanism. The arguments are presented in electrostatic units but, where pertinent, the results are given in units more common in literature for atmospheric electricity.

2. CLOUD MODEL

Figure 1 shows the cloud model, which represents a thunderstorm cloud approaching maturity. Air motion is upward through the base; the lower half of the cloud column is a general region of lateral entrainment, while the upper cloud mass is more stable with some mass effusion associated with evaporation as the cloud penetrates into the drier air aloft. No well-organized downdraft is evident. The cloud is essentially water, although glaciation is occurring near the top. The cloud column is of 3-km. radius capped by an approximate hemisphere of the same dimensions.

3. BASIC ARGUMENT

The analysis of the charge distribution is based on an elementary concept. At the center of the cloud system, an electric generator mechanism is assumed which separates charge upward and downward into the charge centers that constitute the primary dipole charge distribution of the thundercloud. The charge accumulation in the upper and lower charge centers increases the radial component of the electric field within and outside the cloud. As both the cloud and the free-air environment are conducting, the increasing radial electric field causes an increasing conduction current flow of that sign to discharge the cloud charge system. At any moment the rate of charge growth of a given charge center is determined by the difference in the charging and conduction currents. This is sketched in figure 2, where the double arrow I indicates the charging current furnished by the thunderstorm generator to the charge center Q; the single arrows, i, indicate the conduction current flowing inward across a surrounding gaussian surface, S. The system is in dynamic equilibrium in the sense that cloud charges would shortly dissipate by the conduction process if the supply current furnished from the thunderstorm generator were to cease.

The above argument is similar to that utilized by Kasemir [11] and others (Gunn [7], Holzer and Saxon [10]). Although it appears obvious that in clouds the lightning discharge may intercede prior to final equilibrium (i.e., prior to the equality of the charging and conduction currents when $dQ/dt=0$), the concept permits a valuable insight into the complex thunderstorm system.

4. ANALYTICAL EVALUATION OF THE CLOUD MODEL CHARGE DISTRIBUTION

The primary thunderstorm dipole is composed of an upper positive charge at 9 km. and a lower negative charge at 5 km. The basic argument is modified in that the current I within the cloud is taken to be the net current across the base of the gaussian surface S in figure 2, that is, the algebraic sum of the thunderstorm's generator current and the vertical conduction current within the cloud. This definition of the charging current permits a readily interpretable evaluation of the cloud charge distribution.

If the region inside the surface S represents a region of charge accumulation, then the growth of charge is determined by the difference of the charging current I and the conduction current across the boundary, so

$$\frac{dQ}{dt}=I-\int \mathbf{i}\cdot \mathbf{ds},$$

where $\mathbf{i}$ is the current density across S. The current density is related to the electric conductivity and field strength by $\mathbf{i}=\lambda\mathbf{E}$, in which case the above relation can be written as

$$\frac{dQ}{dt}=I-\bar{\lambda}\int \mathbf{E}\cdot \mathbf{ds},$$

where $\bar{\lambda}$ is the mean conductivity over S. Using Gauss' law yields the immediate result that $dQ/dt=I-4\pi\bar{\lambda}Q$. If we assume I constant and $Q=0$ when $t=0$, the solution is

$$Q=\frac{I}{4\pi\bar{\lambda}}\left(1-e^{-4\pi\bar{\lambda}t}\right). \tag{1}$$

By the above definition of the charging current, the integrated conduction current across the cloud cross-section (base of the semispherical surface) required by the Gauss' law relation is included in the term I. Thus that portion of the total charge that is bound by electric force lines passing through the central cloud cross-section, together with the total charge in the upper or lower cloud, is not evaluated by (1). The notation Q' will be used in what follows to emphasize the partial nature of the charge evaluated.

Equation (1) emphasizes the marked importance of the electrical conductivity within and about the cloud. As we will see, for a given thunderstorm charging current, the net charge appearing from without the cloud is controlled by the conductivity of the free air surrounding the cloud. The conductivity within the cloud, in turn, determines the leakage current through the cloud and the quantity of charge in the central cloud core. Finally, the supply time required for a cloud charge region to attain a charge within $1/e$ the equilibrium charge is given by $\tau=1/4\pi\bar{\lambda}$ sec.

Within thunderclouds, the value of the conductivity is not established by measurement. (An analysis of the conductivity in thunderclouds is made by Phillips [12] and Freier [6] in this issue.) Measurements in non-thunderstorm clouds show that within both maritime and continental clouds and within both supercooled and warm clouds the conductivity approximates 1/20th to 1/3d the free-air value at the same height (Allee and Phillips [1], Cobb and Phillips [2]). Near the cloud boundary, the conductivity varies with distance from the cloud-air interface within and outside the cloud. If a surface S is taken inside this boundary region of varying conductivity, then the charge Q' within S for final equilibrium is given by (1) as

$$Q'_{core}=\frac{I}{4\pi\lambda_c}, \tag{2}$$

where λ_c is the interior cloud conductivity. This represents the charge within the central cloud that is not bound to the opposing pole of the dipole charge distribution by electric force lines entirely within the cloud.

If a surface S' is taken in the free air beyond the boundary region outside the cloud-air interface, then the mean conductivity over S' is $\bar{\lambda}_a$. The equilibrium net charge within the outerlying surface is again given by (1), so

$$Q'_{net}=\frac{I}{4\pi\bar{\lambda}_a}. \tag{3}$$

This amount of charge is the net charge within the cloud and the cloud boundary region. Since $\lambda_a>\lambda_c$, we see that Q'_{net} represents that fraction of the central core charge not bound to the opposing pole charge within the cloud less an outer screening charge of opposite sign residing at the cloud boundary.

The surfaces can be so defined that the electric field is nearly parallel to the surface generated by the two truncation curves of horizontal cloud cross-section, whereby there is near equality of current flow through the inner and outer surfaces S and S'. It follows that the total screening charge, Q_{sc}, at the cloud boundary is given by the difference of Q'_{core} and Q'_{net}, or

$$Q_{sc}=\frac{I}{4\pi\bar{\lambda}_c}\left(\frac{\lambda_c}{\lambda_a}-1\right). \tag{4}$$

Here Q_{sc} is the total screening charge at the cloud boundary irrespective of the amount of charge bound within the cloud. A similar result has been given by Kasemir [11] and by Gunn [9]. If we recall that $\lambda_a=f\lambda_c$, where f is a factor of from 5 to 20, we see that $|Q_{sc}|\sim Q_{core}$. This ignores the charges $+Q_B$ and $-Q_B$ that are part of the primary dipole charge cores in the upper and lower cloud and bound by electric force lines within the cloud. Since the separation distance between the charge centers of the primary dipole is relatively greater than the radial distances between the core charges and screening charge layers, the magnitude of Q_B should not be so great as to materially alter the result that $|Q_{sc}|\sim Q_{core}+Q_B$.

That the surface charges which exist about the upper and lower central charge cores are comparable to the primary dipole charges as demonstrated by this model is perhaps surprising. It is pertinent to ask where within the cloud boundary region the screening charge distribution occurs. At the cloud boundary the effect of the normal component of the electric field is twofold. First, since the conductivity within the cloud is diminished to a fraction of the free-air value, only a fraction as many ions of that sign repelled from the cloud pass through a given surface cross-section as are received from the incoming attracted ion current. For quasi-stable cloud surfaces, this unbalanced ion concentration will create an electrode layer of non-zero space charge in the free air outside and in the cloud air inside the cloud-air interface. The second effect is the result of the first. Cloud or rain droplets immediately within the peripheral cloud layer in the presence of the electric field and unbalanced ion concentrations become selectively charged by ionic conduction as a result of the nonequal current flow to the polarization charges on the drops. Gunn [9] refers to this process of conduction charging as hyperelectrification and shows that the droplet charge is given by

$$Q=3Ea^2\frac{[(\lambda_+/\lambda_-)^{1/2}-1]}{[(\lambda_+/\lambda_-)^{1/2}+1]}, \tag{5}$$

where a is the droplet radius, and E and (λ_+/λ_-) are, respectively, the electric field and the ratio of the polar conductivities in the vicinity of the drop. For truly unipolar ion concentrations, this reduces to the well-known relation $Q=\pm 3Ea^2$, where the sign is that of the existing ion concentration. The process of conduction charging constitutes a powerful charging mechanism of unquestionable validity. The net effect of the capture of conduction ions along stable peripheral cloud layers is to establish a surface charge at and immediately within the cloud boundary. This deposition of charge on the cloud particles near the cloud-air interface in large part accounts for the measured results from aircraft, showing that potential gradients are small outside the cloud and increase with cloud penetration.

The distribution of space charge carried on the free ions in the electrode layer outside the cloud surface for the quasi-static case considered involves the solution of the set of equations

$$\begin{aligned}
&\text{div } \mathbf{E}=4\pi\rho=4\pi e(n_+-n_-)\\
&\int \mathbf{i}\cdot d\mathbf{s}=\text{constant}=I\\
&\text{div } (n_+k\mathbf{E})=-(q-\alpha n_+n_-)\\
&\text{div } (n_+k\mathbf{E})=-(q-\alpha n_+n_-)
\end{aligned} \tag{6}$$

which has not been obtained here. In equation (6), ρ is the total space charge density, e the magnitude of the ionic charge, n_+ and n_- the polar ion densities, q the rate of ion generation, and α the recombination coefficient, and k the ionic mobility for small ions.

In the absence of the solution, it is still possible to evaluate the upper limit of space charge outside the cloud-air surface and subsequently the limiting minimum total space charge within the hyperelectrified cloud lamina inside the cloud. Consider the steady-state condition outside the upper cloud surface for example, where the radial component of the field is directed outward. If the cloud were infinitely dense, then in the lamina immediately adjacent to the cloud the concentration of positive ions is zero since the positive ions outside the cloud boundary are swept outward by the action of the field and there is zero flow of ions from the cloud. The last term of the final two equations of (6) is then zero and the spatial rate of change in the ion flow is equal to the rate of ion generation. For actual clouds the positive ion density will be reduced, but not zero. The rate of ionization still exceeds the rate of recombination. The positive ion density increases with distance from the cloud-air interface to its equilibrium value at a large distance. The inverse variation occurs with the negative ion concentration, which increases above the far-field equilibrium value with decreasing distance toward the cloud surface as a result of the reduction in the rate of recombination. At the cloud-air interface the total conductivity λ is greater than the negative component of the conductivity λ_-, which in turn exceeds the negative conductivity in the free air remote from the cloud boundary; i.e., at the cloud surface $\lambda>\lambda_->\lambda_a/2$, where $\lambda_a/2$ is the equilibrium value of the negative conductivity in the free atmosphere outside the boundary region. Thus the limiting value of the net total charge residual within the upper cloud-air interface is, from (3),

$$\begin{aligned}
Q'&<\frac{I}{4\pi(\lambda_a/2)}\\
&<2Q'_{net}.
\end{aligned} \tag{7}$$

From this the charge residing inside the cloud-air surfaces within the hyperelectrified layer is

$$Q_{hyper}>Q'_{core}-2Q'_{net}, \tag{9}$$

or

$$Q_{hyper}>\frac{I}{4\pi}\left(\frac{1}{\lambda_c}-\frac{2}{\lambda_a}\right). \tag{10}$$

The limiting shielding charge residing in the electrode region outside the cloud in turn is

$$Q_{ext}<Q'_{net}=\frac{I}{4\pi\lambda_a}. \tag{11}$$

These results show that the primary shielding charge lies in the hyperelectrified layer inside the cloud boundary. It should be emphasized that the total charge in the hyperelectrified layer is in part the charge directly attributable to the unbalance in the polar ion concentrations inside the cloud surface and is not carried wholly on the cloud particles and precipitation.

By equation (1), the time required for the cloud system charge distribution to attain a charge of $1/e$th the equilibrium value is $\tau=1/4\pi\lambda$. Since $\lambda_a>\lambda_c$, we see at once that the growth of charge in the shielding layers is controlled by the rate of growth of charge in the central core charge centers. Thus the charging time for the primary dipole distribution and for the shielding layers is given by $\tau=1/4\pi\lambda_c$.

5. NUMERICAL EVALUATION

In this section a numerical evaluation based on the preceding analysis is given of the charge distribution within the quasi-static cloud model. It is convenient to choose the surfaces S and S' within and outside the cloud as concentric semispherical surfaces of 2.5-km. and 4-km. radius, respectively, which center on the primary dipole charge centers of the cloud at 5-km. and 9-km. heights. The semispherical surfaces are truncated horizontally near the mid-cloud height along the curve of intersection with a vertical axis cone of $\pi/4$ half angle with apex at the center of the respective charge centers. An example of the exterior surface S' of the upper cloud is evident in figure 2. This allows the surfaces generated by the two truncation curves for the upper or lower cloud gaussians to be *approximately parallel to the electric force* lines as required by the argument leading to (4). From lightning data, I is assumed to be one ampere.

The free-air value of the conductivity as a function of altitude can be formulated by $\lambda=\lambda_h \exp 2kz$, where λ_h is the conductivity at height $z=h$ and $k=0.11\times10^{-5}\text{cm.}^{-1}$ At the heights of the 9-km. and 5-km. charge centers of the primary dipole, the free-air conductivity is $\lambda_{9a}=5\times10^{-3}$ e.s.u. and $\lambda_{5a}=2\times10^{-3}$ e.s.u. based on published data (Woessner et al. [16]). For the quasi-static cloud model, the interior cloud conductivity is assumed to be reduced to 1/10th the free-air value in the lower negative charge region and to 1/5th for the upper cloud region. In taking the factor of 1/5 for the upper cloud region, cognizance is taken that the coagulation and diffusion processes have already been effective in reducing the cloud particle population. Using these factors yields the interior cloud conductivities at the two heights of the charge centers as $\lambda_{9c}=1\times10^{-3}$ e.s.u. and $\lambda_{5c}=2\times10^{-4}$ e.s.u. The variation with height within the cloud is defined by the same exponential factor as given above for the free-air conductivity variation.

UPPER CLOUD CHARGE DISTRIBUTION

If we take the spherical surface S of radius 2.5, km. centered at the 9-km. height of the upper charge center (i.e., ½ km. inside the cloud-air interface), the mean conductivity evaluated over S is $\overline{\lambda}_{9c}=1.12\times10^{-3}$ e.s.u. Then the core charge within the central upper core volume enclosed at equilibrium is $Q'_{core}\sim70$ C. by (2). In turn, if S' is of similar shape and of radius 4 km. (i.e., 1 km. outside the cloud-air interface) then the mean conductivity over S' is $\overline{\lambda}_{9a}=7.07\times10^{-3}$ e.s.u. and the net charge within the outerlying surface by (3) is $Q'_{net}\sim11$ C. The total screening charge in the region of the cloud boundary is $Q'_{core}-Q'_{net}\sim59$ C. The mean radial field at the $r=2.5$ km. and $r=4$ km. surfaces is given by $\overline{E}=4\pi Q'/S$, whence $\overline{E}_{r=2.5}=1665$ v./cm. and $\overline{E}_{r=4}=73$ v./cm. The field increase across the boundary layer amounts to nearly 1600 v./cm. Of the total screening charge distribution of 59 C. the charge existing outside the cloud-air interface as a result of the unbalance in the concentration of small ions is less than 11 C., while the total charge residing inside the cloud-air surface within the hyperelectrified shielding layer by (9) is $Q_{hyper}>48$ C.

LOWER CLOUD CHARGE DISTRIBUTION

The lower cloud charge distribution and mean electric field are approximated in a similar manner. Within the cloud at a radius of 2.5 km. the average conductivity over the similarly defined but inverted surface S is $\overline{\lambda}_{5c}=1.92\times10^{-4}$ e.s.u. The charge within the cloud core is from the $Q'_{core}\sim413$ C. In the free air 1 km. from the lower cloud-air surface, $\overline{\lambda}_{5a}=1.93\times10^{-3}$ e.s.u. and the net charge in the lower cloud system is $Q'_{net}\sim41$ C. Thus the total screening charge in the region of the cloud boundary is $Q_{sc}\sim372$ C. From these values the mean radial electric fields within the clouds at 2.5-km. radius and outside the cloud at 4-km. radius are $\overline{E}_{r=2.5}=6880$ v./cm. and $\overline{E}_{r=4}=270$ v./cm., respectively. Within the shielding charge distribution, the charge $Q_{hyper}>331$ C. lies within the cloud-air interface while the charge existing outside the cloud as a result of the unbalanced ion concentration is $Q_{ext}<41$ C.

The resulting charge distribution within the cloud system may be summarized as follows: If Q_B represents the intra-cloud bound charge, then the primary dipole central charges of $+(70\text{ C.}+Q_B)$ and $-(413\text{ C.}+Q_B)$ are located at 9 km. and 5 km., respectively. The positive charge core of the upper cloud is masked by a negative charge sheath of 59 C. which exists primarily within the cloud-air interface. Of the total masking charge of 372 C. about the lower negative charge, something less than 41 C. occurs as a result of the free ion unbalance outside the cloud, while some 331 C. is distributed at and within the cloud surface. To an observer distant from the cloud the charge distribution appearance is that of a positive dipole having 11 C. in the upper center and near three times this magnitude, or 41 C., in the lower center. The charge distribution within the sheathing layers will reflect the fact that the sheathing layer intensity depends on the radial component of the electric field. Thus the sheathing layer thickness is minimum along the central cloud boundaries where the electric force lines are essentially parallel to the cloud boundary and maximum across the upper and lower cloud boundaries where the true radial field is most intense. The asymmetry of charge would clearly result if the true dipole field distribution above the conducting earth were evaluated.

6. STABILITY OF THE CLOUD SURFACE AND ITS RELATION TO THE CHARGING TIME

It is clear that to establish the surface charge distribution the surface of the cloud must be geometrically stable over a time period commensurate with the charging time. Based on our estimates of the conductivity in clouds, the charging times for the upper and lower centers determined from equation (1) are $\tau_9=71$ sec. and $\tau_5=413$ sec. respectively. Since in the present cloud model, the cloud dome is viewed as a generally expanding volume with some mass effusion, it is appropriate that the upper cloud may be considered stable; that is, the cloud upper surface is geometrically constant for the period $\tau_9=71$ sec.

For the lower cloud the greater charging time and more rapid radial cloud motion through the cloud boundary region may cause the screening charge to be distributed to considerable depths inward from the cloud surface. Cloud droplets near the cloud surface will acquire charge by the hyperelectrification mechanism during the charging period. With convective motion the screening charge distribution so established on the cloud droplets will be carried along with the droplets. Thus for example, if the vertical motion upward through the cloud base is at the rate of 2 m./sec., then during the charging period $\tau_5=413$ sec. the sheathing layer thickness within the lower cloud will be expanded 828 m. upwards.

The analysis of the charge deposition within the sheathing layer and the charge transfer by convective cloud motion will be treated more fully in succeeding papers. It is worthwhile to note here that the charging times of 71 sec. and 413 sec. are determined by the magnitude of the cloud conductivity as outlined in the previous section. If one considers the time required for a *readjustment* of the surface screening charge following a sudden shift in the central core charge, such as may result at the moment of lightning disruption, then the time constant is determined primarily by the *free-air conductivity*. Thus for boundary layer charge readjustment, the time constant for the upper cloud is $T_{9a}\sim 11$ sec. and for the lower cloud approaches $T_{5a}\sim 41$ sec. These are the time constants that are important when considering recovery times of electric fields observed outside the cloud following lightning discharges.

7. DISCUSSION OF THE QUASI-STATIC THUNDERSTORM MODEL

A primary result of the preceding analysis is that given a thunderstorm generating mechanism that separates charge to the upper and lower central charge cores, boundary layer charges of large magnitude develop. Only two assumptions are basic to the argument: first, a thunderstorm generator is present; second, the electrical conductivity is reduced in the cloud mass from its free-air value. Following this, the development of the sheathing charge distributions is the consequence of the growth of the interior cloud charge. The charges developed about the cloud-air interface are composed of two parts: a net charge arising from the inequality of the polar ion concentrations and a net charge deposited on cloud particles as a result of ionic conduction. The charge distribution of a cylindrical cross-section vertically through the cloud is that of a double dipole. The lower and upper cloud each have a negative dipole charge distribution; the necessary asymmetry of charge in the negative dipole is such, however, as to make the overall charge distribution of the cloud system that of the observed positive dipole of thunderstorms.

A comparison of these results with the properties of real storms must be made with caution. In thunderstorms, the complexities of the storm dynamics, geometry, and frequent discharges are superimposed on the basic simplicity of the quasi-static model. However, the gross primary dipole charge distribution recognized to exist in thunderstorms and the time constants for charge transfer to cloud boundaries which are determined by the values of the *free air* conductivities are such as to insure that the sheathing charge distributions are true features of real storms. The aircraft measurement data showing that a tenfold increase in the intensity of the electric field occurs commonly within storms is corroborative evidence.

The value of the charges distributed in the quasi-static model appear not overly large when compared with the charges neutralized by cloud lightning strokes reported by Takeuti [14]. The reported thundercloud electric fields measurements (Gunn [8], Fitzgerald and Cunningham [5]), however, would seem to indicate that fields of 3000 v./cm. and greater are not as general within the cloud as the present model suggests. The calculated 6880-v./cm. field inside the lower cloud boundary approaches that required to initiate the lightning discharge, perhaps suggesting that the charge accumulation is field-limited.

The positive charge distribution (+4 C. in the Simpson-Robinson model) is explained completely by the lower positive sheathing charge distribution at the cloud base. The lower charge is usually interpreted to be small and to be contained within a small region of the cloud. In reality the positive charge is evidently large and dispersed throughout a considerable volume within the lower cloud mass.

A related phenomenon is the reversal of the electric field at the ground beneath storms from large positive values (negative charge overhead) prior to the lightning stroke to large negative values (positive charge overhead) immediately following the ground stroke. Immediately following the stroke the electric field as measured at the ground reflects the aggregate of the charge distribution aloft. Since the upper positive charge of the central core primary dipole is more distant from the observation point beneath the storm we should expect the field following the stroke to be of small magnitude. This is apparent when we recognize that a large portion of the upper center positive charge is bound to negative charge in the upper sheathing layer. Thus the large field reversal and near-equality of the measured field before and after the stroke is most readily explained by the existence of a comparatively large but distributed positive charge within the lower portions of the storm.

Similarly, the meandering lightning discharges observed to traverse horizontally within the base of thunderclouds are most easily explained as the discharge of a central negative charge center to the positive sheathing charge region. Here, however, the gathering and distributing mechanisms of the lightning discharge are probably controlling for the length and character of the visible discharge.

The existence of the negative sheathing charge distribution in the cloud top has been questioned by several investigators but as yet no definitive measurement data are available. The very short time constant required to establish the sheathing distribution at the height of the storm tops and the basic argument of conduction flow emphasize that a negative charge sheathing layer within the uppermost cloud heights exists. It is important that aircraft measurements be made of the net space charge, both in the cloud tops and in the cloud bases to establish the generality of the sheathing distributions within the cloud boundary regions of thunderstorms. The existence of moderately large charge accumulations in cloud boundary layers has considerable and important implications regarding thunderstorm electrification.

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